EQUIPMENT AND PROCEDURES FOR ON-SITE TESTING OF PV PLANTS AND BIPV

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ABSTRACT: Actual system performance of a PV system can differ from its expected behaviour.. This is the main reason why the performance of PV systems should be monitored, analyzed and, if needed, improved on. Some of the current testing procedures relating to the electrical behaviour of PV systems are appropriated for detecting electrical performance losses, but they are not well-suited to reveal hidden defects in the modules of PV plants and BIPV, which can lead to future losses. This paper reports on the tests and procedures used to evaluate the performance of PV systems, and especially on a novel procedure for quick on-site measurements and defect recognition caused by overheating in PV modules located in operating PV installations.

Keywords: System Performance, Plant Control, BIPV, Qualification and Testing, IR thermal performance

1 INTRODUCTION

During the last 10 years, grid-connected photovoltaic (PV) systems totalling a nominal power of more than 100 GW have been installed all over the world [1]. In order to make possible to sustain this high installation rate in the future, it is needed to ensure a proper operation of the PV systems that guarantees their good performance. Therefore, testing and monitoring procedures are critical to check whether the PV systems' actual performance is in line with expected behaviour. Otherwise, they should be improved on, by repairing or replacing the faulty devices.

Typical testing procedures to evaluate the performance and quality of PV systems can be divided in two groups: electrical procedures and other procedures. The electrical procedures aim to determine the behaviour of PV arrays and PV inverters, as well as their compliance to the established international standards [2]. Some of the usual electrical tests that should be carried out in the field on PV installations are:

- Measurement of the PV array IV curve [3]. This characteristic is very useful to verify if the actual array power is coherent with the nominal power installed (sum of the power of all the modules in the array). It allows detecting if a set of modules has a power below the manufacturer's datasheet (or flash-list) and/or if a string is disconnected (due to burnt out fuses, disconnected cables, defective PV modules resulting into open-circuit conditions for string they belong to, etc.). This test can also notify on aging and degradation with time and/or anomalies such as shading and potential induced degradation (PID), etc. [4] [5]. There are several commercial devices that are designed to measure IV curves [6], and detailed schemes have been shared that describe how to build our own IV tracer [7] (Fig. 1).
- Measurement of the PV inverter efficiency. This test is carried out simultaneously at the input and at the output of the PV inverter, and it is useful to verify if the actual inverter's behaviour complies with the manufacturer's specifications. It can be performed with a wattmeter [8].

Figure 1: 100 kW I-V curve tracer implemented by CL SENES in the framework of the PVCROPS project. It is based on IGBTs and capacitors [7].

- Measurement of the PV system's performance. This test allows knowing in detail the instantaneous behaviour of the PV system and its performance under abnormal conditions, such as shading, inverter saturation, strings disconnection, etc. [8]. It can also be achieved with a wattmeter.

  As an alternative, CL-SENES has implemented a portable SCADA tool based on split-core distributed DC and AC current/voltage sensors connnected in series by a cable line using RS-485/Modbus protocol (Fig.2).

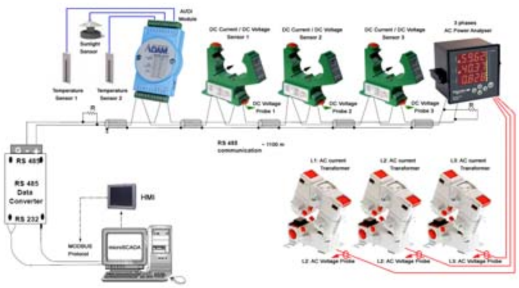

Figure 2: Portable SCADA tool for DC and AC measurements developed by CL SENES.

- Measurement of the PV array insulation resistance [2]. It is very important to ensure the electrical safety of the system, because ground faults represent safety hazards to personnel. In fact, inverters typically are equipped with an insulation alarm that warns when this defect appears [9].
- Measurement of PID. At a later stage, it is common to carry out on-site tests to determine if modules are affected by PID. This is usually done during night hours with the help of a power source and a CCD camera [10], but new procedures that can be achieved with only a power source have been proposed [11].

The other procedures (other than electrical) mainly consist of visual inspections that aim to detect defects on civil works, structures, PV modules, connection boxes, inverters, etc. [12]. Some of these defects are the hot-spots in PV modules, which are invisible for the naked eye. Nevertheless, they can be detected with infrared (IR) imaging. In the last years, IR cameras have become in a very valuable device for detecting hot-spots [13].

Larger PV plants and Building Integrated PV (BIPV) are making more difficult and more time consuming to complete on-field IR test on PV modules to assess the good performance of the installation.

In this contribution, we present a novel procedure to quickly detect hot-spots in large PV plants and BIPV of difficult access through IR imaging. This procedure makes use of hardware composed of a PV drone, a microcontroller, and an IR camera. We show the results of the application of this procedure on the detection of several defects present at a 150-kW PV plant located in Bulgaria.

2 METHODOLOGY

2.1 Equipment

This procedure makes use of three main hardware components:

- A PV drone;
- An open-source microcontroller;
- An IR camera.

Recently, the concept of open-source software (free-sharing of computer code) has evolved to incorporate open-source hardware (open-sharing of hardware designs). Rapid advances in programmable microcontrollers have resulted in new control and data logging systems and can offer unique low-cost solutions [http://arduino.cc]. One of the open-source projects used by us called Arduino consists of an open development platform based on C++ compiler. As an open-source project, the Arduino benefits from the collective efforts and expertise (libraries and sample code) of free developers from all around the world. In addition to built-in A/D converters and timers for measuring analog voltage signals, PWM outputs, I^2C and SPI standardized communications protocols are available for interfacing to digital sensors, motors, data transmitters or microSD memory cards. Besides, recent Arduino libraries provide pipeline to LabVIEW environment which ensure huge flexibility for data logging and data manipulation.

One promising method for inspecting PV installations is the use of an autonomous photo/video scanning on the strings of PV modules from the air, with the help of an unmanned aerial vehicle (UAV). Recent small multirotor helicopters have enough lifting power to carry camcorders, Hi-Res cameras, IR cameras as well as video transmitters. The success of open-source avionics allows constructing useful tools for the PV testing, monitoring and inspection. This unmanned testing option is of special interest for some applications such as large PV plants, PV roofs or PV facades, where it is difficult, risky or time-consuming to reach active PV surfaces.

The development of UAV electrical quadrocopters has started recently, because controlling 4 independent rotors has proven to be a difficult task, and it is impossible without precise microprocessor control [http://diydrones.com]. The quadrocopter needs a gyroscope sensor, to be able to measure the angles and to send feedback to the main PID controller for position stabilization and for control of linear velocity. Control precision of altitude and gyroscope drift is improved by adding more sensors: 3-axis accelerometer, barometer and 3-axis magnetometer. Successful experiences have been reported from academia, UAV industries, and radio-control (RC) hobbyists [14]. In this context, open-source projects on UAV allow fast development processes because new features can be tested not only by the developer. Feedback is provided in real time from various conditions and configurations, which makes open-source software more robust in a relatively short period of time.

Our experience reported here is based on in-home assembled X-shape quadrocopter, Arducopter controllers, Mission-Planner Ground Station and visible, near-IR and IR cameras. Numerous open-source projects and videos [15,16] have contributed to our team to complete our engineering work. The main platform, Arducopter, is a quadrocopter - autopilot project based on the Arduino framework and developed by endless efforts of engineers from worldwide [17]. Fig. 3 shows a picture of our quadrocopter.

Figure 3: Quadrocopter with and IR camera and a visible camera for monitoring a PV installation.

In our work, IR images have been achieved with low-weight IR camera. Experience using infrared sensors to monitor PV module temperature has shown that they work well in hot environment, and that they provide accurate temperature measurements.

As visible on Fig. 3, our robo-copter is equipped with an analog visible camera (camera resolution of 600 TVL –TV lines– is sufficient to detect optical imperfections on the modules at first glance) for video transfer from drone to a ground station. So, on a screen this camera can be monitored to check the PV modules remotely. It also has an 80 x 60 pixels modified infrared camera that takes pictures following a command from the ground through a radio controlled trigger.

A sophisticated radio controlled (RC) flying device operating at 3 frequency ranges has been assembled. It can be manually controlled from the ground by 2.4 GHz RC control station using 4 channels for Throttle, Yaw, Pitch and Roll. Other channels are configured for video switching and still picture triggering. Video transmission from the air to ground is based on 5.8GHz wireless video-link, while additional 433 MHz wireless connection can upload to Arduino controller waypoints with GPS coordinates for autonomous flying missions.

Figure 4: Quadrocopter flying mission planned for a 150 kW PV plant.

2.2 Procedure

The visual and thermo-graphic inspection with the drone is as follows: first, the drone does its flying mission and records a video stream by a digital video recorder (DVR) at the ground station. Besides, the person who is supervising the drone during the flight can both recognize suspicious PV modules and take thermo-graphic pictures (the operator triggers the IR camera using RC commands). Then, on the ground the operator checks the video and the IR pictures. If a defect is recognized in a PV module, the operator goes directly to its location to take more detailed pictures. Thus, the operator avoids having to walk the entire facility on foot looking for defects and should only review those suspected modules detected by the drone. This method is less time-consuming especially in large PV plants and in BIPV of difficult access.

Figure 5: Quadrocopter during the inspection flying mission above the array PV modules.

3 RESULTS

We show the results of the application of this procedure on the detection of several defects present at a 150-kW PV plant located in Bulgaria. A flying mission for a 150-kW PV plant monitoring is shown on Fig.4. This mission planning involves 22 waypoints for zig-zag trajectory exactly above the PV rows, starting from the NW corner of the PV installation and flying at 5 m altitude. The useful flight time is about 15 min with fully charged batteries, which is large enough for inspection all the PV installation. Fig. 5 shows the quadrocopter in flight during the mission.

Fig. 6 to Fig. 11 show several defective modules detected during the flight mission shown in Fig 4.

Fig. 6 shows the worst visual defect detected in the on-field PV testing: a picture taken with the drone in which a module has its front glass broken.

Figure 6: Picture recorded during the drone flight: a module has its front glass broken.

Fig. 7 shows a back picture of this module taken on-site: the internal layers and contacts are burnt. Fig. 8 shows the IR picture of the back of this module: there is a hot-spot reaching more than 83 ºC.

Figure 7: Picture of the back of the Fig. 6 module taken on site. The internal layers and contacts are burnt.

As the right front-side busbar of the solar cell is evaporated (Fig. 6 and Fig. 7) all the current generated by the cell flows through the left busbar and this part of the cell is overheated.

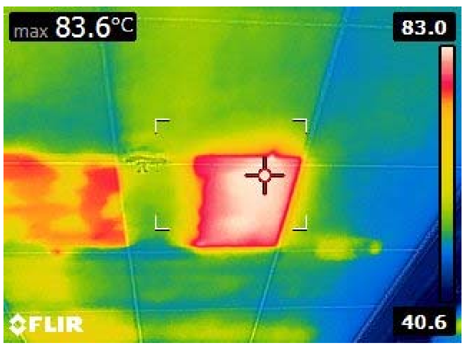

Figure 8: Thermographic picture of the back of the module of Fig.5 and Fig. 6. This module has a hot-spot reaching more than 83 ºC and half of the cell affected is overheated.

Fig. 9 and Fig. 10 show other visual defects initially detected by the drone during its panoramic flight and snapshots taken in details later by Hi-Res camera: a cell-

Figure 9: Cell cracked detected on the corner of a PV module.

crack located on the corner of a PV module and electro-corrosion of busbar due to encapsulation problems: rainwater has reached the internal layers of the module.

Finally, on Fig. 11 is shown the IR picture taken from the drone to detect possible internal defects in the PV

Figure 10: Electro-corrosion of the busbar due to rainwater which has reached the internal layers of the module.

plant modules. Temperature differences in solar cells above 10 ºC could be an early indication of accelerated PV module degradation [18].

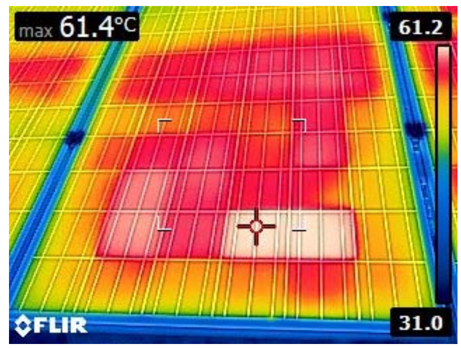

Figure 11: IR picture taken from the drone. It shows two solar cells that are hotter than their neighboring cells (above 10 ºC).

4 DISCUSSION

The aim of the drone is to detect failures in modules by airborne small cameras. It should be low-weight, having wide aperture and small energy consumption. The pictures taken are low resolution but they save time for problem detection as well as maintenance cost. More efforts are needed to solve the problems with picture quality due to vibrations.

5 CONCLUSIONS

In this contribution, we present a novel procedure to quickly detect hot-spots in large PV plants and BIPV of difficult access through IR imaging. This procedure makes use of hardware composed of a PV drone, a microcontroller, and an IR camera. We have described a quadrocopter based on open-source platforms (ARDUINO technology) used for large-area PV inspection. Visual and thermo-graphic inspection can be implemented with this device. The main result of this testing procedure is a shorter time for visual and thermo-graphic inspection of a PV installation than the standard procedure (do these inspections by walking through the entire installation). We show the results of the application of this procedure on the detection of several defects present at a 150-kW PV plant located in Bulgaria. Several PV modules failures were detected and reported.

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